QUASI-MOLECULAR SATELLITES OF LYMAN BETA IN THE SPECTRUM OF THE DA WHITE DWARF WOLF 1346[1]

D. Koester
Institut für Astronomie und Astrophysik, Universität Kiel, D–24098 Kiel, Germany. E-mail: koester@astrophysik.uni-kiel.d400.de

D. S. Finley[2]
Eureka Scientific, Inc. 2452 Delmer St. Suite 100, Oakland, CA 94602

N. F. Allard[3]
Observatoire de Paris-Meudon, F–92195 Meudon, France

J. W. Kruk
Johns Hopkins University, Center for Astrophysical Sci., Baltimore, MD 21218. E-mail: kruk@hut4.pha.jhu.edu

and

R. A. Kimble
NASA/GSFC, Greenbelt, MD 20771. E-mail: kimble@stars.gsfc.nasa.gov

ABSTRACT

We present new FUV/UV observations of the DA white dwarf Wolf 1346 obtained with the Hopkins Ultraviolet Telescope. The atmospheric parameters of this object are estimated from a fit of model atmospheres to several optical spectra to be $T_{\rm eff} = 20000$ K, $\log g = 7.90$. From the optical spectrum this star is a normal DA without any indications for chemical elements other than hydrogen. The hydrogen line Lβ, however, shows a very unusual shape, with a steep red wing and two absorption features on this wing. The shape is reminiscent of the effects of quasi-molecular line broadening, as observed in Lα in cooler DA white dwarfs. We show that this is indeed the correct explanation, by identifying 4 quasi-molecular satellites caused through perturbations by the H^+ ion (H_2^+ quasi-molecule). The steep red wing is caused by the exponential decline of the line profile beyond the satellite most distant from the line center at 1078 Å.

[1]Based on observations obtained with the Hopkins Ultraviolet Telescope and optical observations obtained at the DSZA Calar Alto

[2] Center for EUV Astrophysics, University of California, Berkeley, CA 94720. E-mail: david@cea.berkeley.edu

[3] CNRS Institut d'Astrophysique, F-75014 Paris, France. E-mail: allard@iap.fr

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1. Introduction

Throughout the recent history of astronomy it has happened repeatedly that the opening of a new observing window into space has lead to discoveries that were not expected. Just in the field of white dwarfs the systematic exploration of the UV window has brought unexpected surprises. We mention just a few out of a large number: the discovery of metal features in hot DA, very strong carbon lines in DC white dwarfs, which show no features at all in the optical, and quasi-molecular satellites in cool DA, which were expected to show just a simple Stark broadened Lα line.

One of the least explored spectral windows remains the FUV region, roughly defined as 912 - 1215 Å, the region from the Lyman edge to Lα. While the interstellar matter is quite transparent at these wavelengths, as opposed to the region below the Lyman edge, progress has been slow due to technological difficulties in the production of mirrors and gratings. This situation is improving recently with projects like ORFEUS (Orbiting Retrievable Far and Extreme Ultraviolet Spectrograph; Grewing et al. 1991; Hurwitz & Bowyer 1991) and HUT (Hopkins Ultraviolet Telescope, Davidsen et al. 1992). In this paper we report on an observation of the bright DA white dwarf Wolf 1346 (WD2032+248), obtained with the HUT instrument on a flight in 1995. The observation was part of an Astro-2 Guest Investigator program (Finley, Kimble, and Koester) aimed at studying the Stark broadening of the higher Lyman lines in DA. While several hotter DA show the whole Lyman spectrum compatible with symmetrical Stark broadened profiles without any unexplained features, Wolf 1346 at 20000 K has a Lβ line with a strong asymmetry, a very steep red wing, and absorption features in the wing near 1060 and 1078 Å. We demonstrate below that all these features are due to quasi-molecular H_2^+ absorption (or broadening of Lβ by protons as perturbers), very similar in nature to the 1400 Å feature observed at lower temperatures in the red wing of Lα.

2. UV/FUV observations with the Hopkins Ultraviolet Telescope

Our FUV spectra were obtained with the Hopkins Ultraviolet Telescope (HUT), one of the instruments in the Astro-2 mission that was flown as an attached space shuttle payload in March, 1995. The initial observation of Wolf 1346 was made on 5 March 1995. The spectrum contained wholly unexpected features in the Lyman lines that were so unusual that concerns were raised that some anomaly may have occurred during the observation. Consequently, the real-time scheduling capabilities of Astro-2 were utilized to reobserve Wolf 1346 on 14 March. The two spectra were

virtually identical, and no other white dwarfs showed the unusual features, confirming that the features were intrinsic to Wolf 1346.

The data reduction process included correcting for pulse pile-up; subtracting dark counts, scattered light, and second order light; flat-fielding; and correcting for time-dependent throughput changes during the mission. The pointing during the observations was such that some light was lost due to the target being near the edge of the aperture during much of the exposures. Hence, an additional normalization correction was made using the count rates obtained during the times the target was fully within the aperture. The spectra were fluxed using the instrument sensitivity determined in flight using observations of HZ 43 and a model computed with Koester's atmosphere codes. Finally, the background was subtracted using sky exposures taken during target acquisition, and the two spectra were coadded. The data reduction process and in-flight calibration are detailed in Kruk et al. (1995). The combined HUT spectrum is shown in Fig. 1 and compared

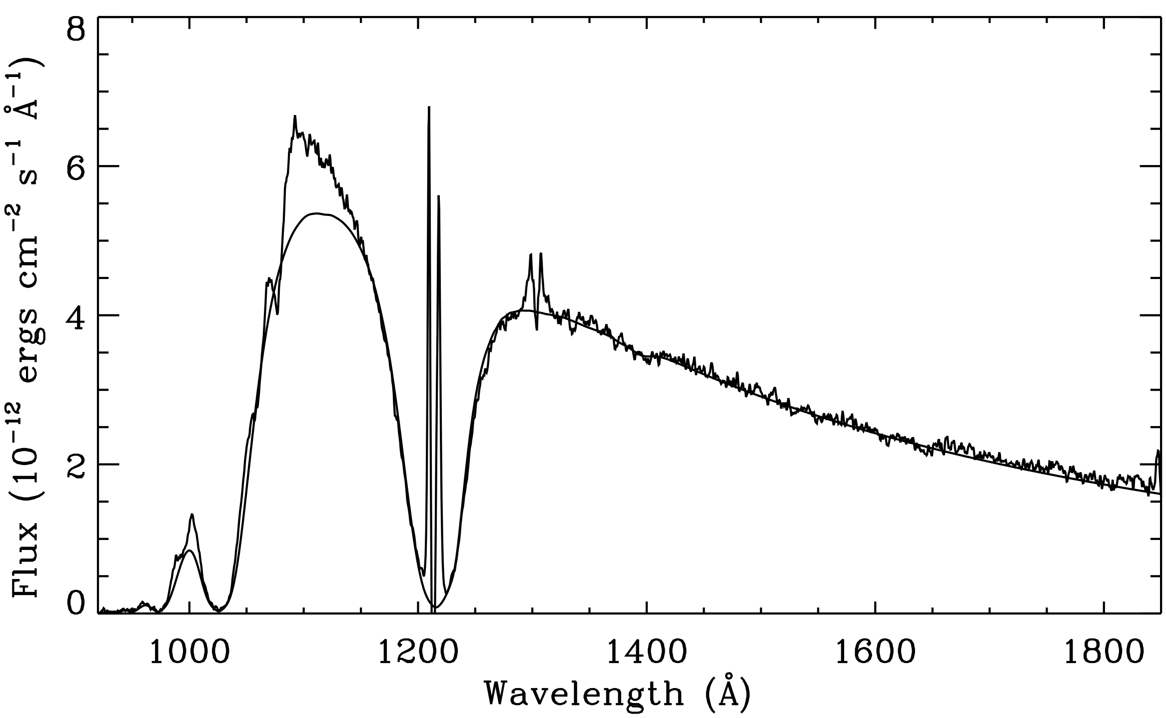

Fig. 1.— Background-subtracted HUT spectrum of Wolf 1346, compared with a theoretical spectrum using standard Lβ Stark broadening. The Lα and OI airglow lines at 1216 and 1304 Å could not be subtracted cleanly due to the decline in sensitivity in those lines through the mission.

with a model of our atmosphere grid, using standard Stark broadening. The model was convolved with the instrument resolution (which varied as a function of wavelength) for comparison with the

observed spectrum. The spectrum was smoothed with a 2-pixel (1 Å) FWHM Gaussian, as was the model. The model was scaled using the published V magnitude of 11.53 (Cheselka et al. 1993) and the relation $f_\lambda(5490\ \text{Å}) = 3.61\ 10^{-9}/10^{0.4 m_V}$ (Finley, Basri & Bowyer 1990). The model required scaling by an additional factor of 1.03 to match the continuum flux between 1350 Å and 1650 Å.

The model does not reproduce the steep red wing of Lβ. In addition, there are two unexplained absorption features on the observed wing at 1060 and 1078 Å. On the red wing of Lα a weak indication of the 1400 Å H_2^+ satellite is visible in both the model and the observation. The HUT effective area (Kruk et al. 1995) is smooth in the 1060 – 1080 Å region. Furthermore, the observed spectra of the hotter DA that were observed agree quite well with the models (Kruk et al. 1995), clearly demonstrating that the Lβ features are not calibration artifacts, but are instead intrinsic to Wolf 1346.

3. Optical observations and stellar parameters

With a visual magnitude of 11.53, Wolf 1346 is a very bright white dwarf and has therefore been included in a number of recent analyses. Bergeron et al. (1992) give 19980/7.83 ($T_{\rm eff}$/log g), Finley et al. (1996) 19960/7.83, and Kidder (1991) 20400/7.90. We have obtained 3 spectra with high S/N at the 2.2m telescope of the DSAZ observatory at Calar Alto in September 1995, and the analysis with a set of model atmosphere grids gives 19500/7.96. Fig. 2 shows the Balmer line profiles from one of these observations together with the best fit model. The fitting procedure included adjusting the models at continuum points to correct for the non-perfect calibration of the observed spectrum, then simultaneously fitting the Hβ – H9 lines, including small sections of adjacent continuum. This means that the fit was determined essentially by the Balmer line profiles only. The formal errors of our fits are very small, comparable to those obtained by the other studies. The slope of the spectrum before adjustment of the continuum – while not totally reliable – indicates that the temperature could perhaps be a bit higher, as indicated by the other results. In any case, the scatter of these determinations indicates that systematic errors are probably higher than the formal errors determined by the least-squares fits, and we adopt very conservatively the following values and ranges for our further study: $T_{\rm eff} = 20000 \pm 500$ K, log $g = 7.90 \pm 0.10$.

4. Quasi-molecular line broadening of Lβ by protons

In the model used for the description of this line broadening, the interaction of the absorbing hydrogen atom in the ground state with the perturbing proton is considered as the temporary formation of a quasi-molecule, in this case the molecular ion H_2^+. The perturbation of the energy levels is then given by the adiabatic potential energy curves of this molecule.

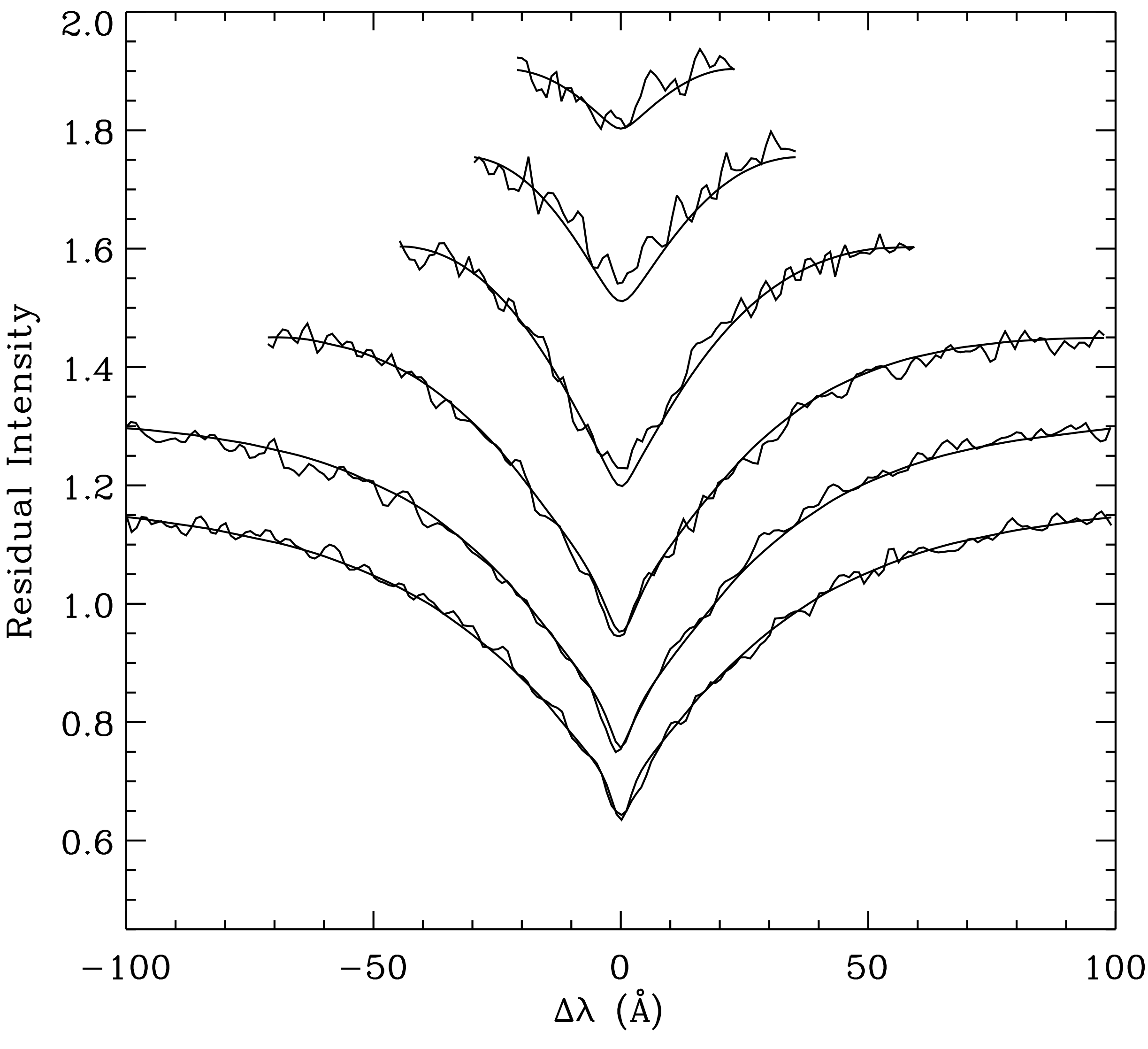

Fig. 2.— Balmer line profiles of Wolf 1346 and the best fitting model with $T_{\rm eff}$ = 19504 K, log g = 7.96. Lines shown are Hβ through H9.

The approach is based on the unified theory of Anderson & Talman (1956) and has in recent years been considerably improved through the work of N. Allard and J. Kielkopf (Allard & Kielkopf 1982, 1991; Allard & Koester 1992; Kielkopf & Allard 1995). A comprehensive recent review of these calculations is Allard et al. (1994).

In these papers the interest was concentrated on the line Lα, because previously unknown features in the IUE spectra of a number of cool DA white dwarfs had been identified by Koester et al. (1985) and Nelan & Wegner (1985) as quasi-molecular satellites of Lα due to perturbations with protons and the neutral hydrogen atom. The application of the new profiles to IUE and HST/FOS spectra has resulted in much improved fits for the UV spectra of cool DA white dwarfs (e.g. Koester & Allard 1993; Koester et al. 1994; Bergeron et al. 1995) and to the identification of the famous 1600 Å feature in the λ Bootis stars as due to the H_2 quasi-molecule (Holweger et al. 1994).

It was therefore quite natural to suspect similar physical effects to be responsible for the strange Lβ profile in Wolf 1346. In this case, the situation is simplified by the fact that at the high temperature of this object the only possible perturber is the proton. We have therefore used essentially the same methods and program codes as described in Allard et al. (1994) and applied them to the transitions corresponding to Lβ, that is between those molecular states that asymptotically (at large internuclear distance) correspond to the first and third energy levels of the isolated hydrogen atom.

The 2 states corresponding to n=1 and 12 states corresponding to n=3 are are listed by Ramaker & Peek (1972, RP). From the transition rules, and from the dipole moments calculated by RP, it is apparent that there are 8 dipole-allowed transitions. We list these transitions in Table 1, together with some relevant information that will be discussed below. The relative weights tabulated for the individual transitions were determined from the Stark broadening calculations of Underhill & Waddell (1959). The potential energy curves for all these states are given by Madsen & Peek (1971). The numerical calculation of the correlation functions for all transitions and the 8 individual contributions to the line profile lead to the following results: each of the 4 transitions contributing (at larger distance from the line center) to the red wing of Lβ shows a satellite feature; the positions are indicated in Table 1 as differences from the line center ($\Delta\omega$ in cm^{-1}) and also with their positions on the wavelength scale in Å. Even without the calculation of detailed synthetic spectra it is clear that the 2 satellites farthest from the center correspond exactly to the features seen in the HUT spectrum; the other two are weaker and lost in the saturated line center. The blue wing of the line shows no satellites, not even in the individual contributions of the 4 transitions. We therefore show only the red wing, to be able to show more of the interesting details, in Fig. 3.

Readers interested in obtaining line profile data should contact N. Allard or D. Koester.

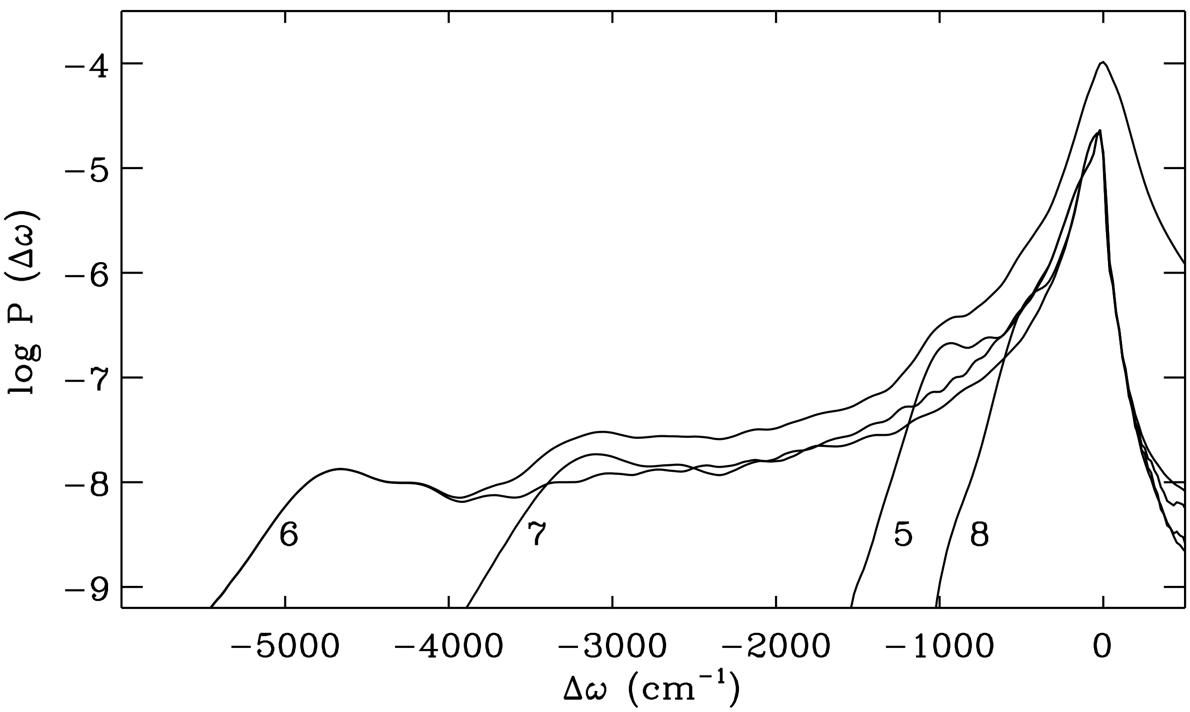

Fig. 3.— Logarithmic line profile for Lβ as a function of distance $\Delta\omega$ from the line center, showing the individual contributions of the 4 transitions contributing to the red wing and the total profile (upper line). The individual contributions are numbered; the numbers correspond to the first column in Table 1. A temperature of 20000 K and proton density of 10^{16} cm^{-3} was used for this calculation.

5. Calculation of model atmospheres and synthetic spectra

The Lβ line profiles have been incorporated in the LTE stellar atmosphere codes for white dwarfs developed and improved by D.K. over two decades. A rather dated description of these codes is in Koester et al. (1979); a more up-to-date version will be given in Finley et al. (1996). The profiles with the quasi-molecular satellites are used consistently for the determination of the atmospheric structure ("line blanketing") as well as for the detailed spectrum synthesis. The line blanketing is important for the Lα satellites at lower temperatures; the effect from Lβ is small. The temperature dependence of the line profiles is small, and for the Lβ line we have used only profiles calculated for a temperature of 20000 K. The absorption coefficient per absorbing atom in the line wing is roughly proportional to the perturber density, whereas the shape of the satellite feature *relative* to the neighboring line wing is independent of density. The satellite will therefore become visible in a spectrum, whenever the line profile is visible out to the position of the satellite. According to our preliminary model calculations for Lβ this is the case in DA white dwarfs between effective temperatures of about 16000 to 25000 K. This agrees with the observational HUT result that all other DA observed are hotter than 30000 K.

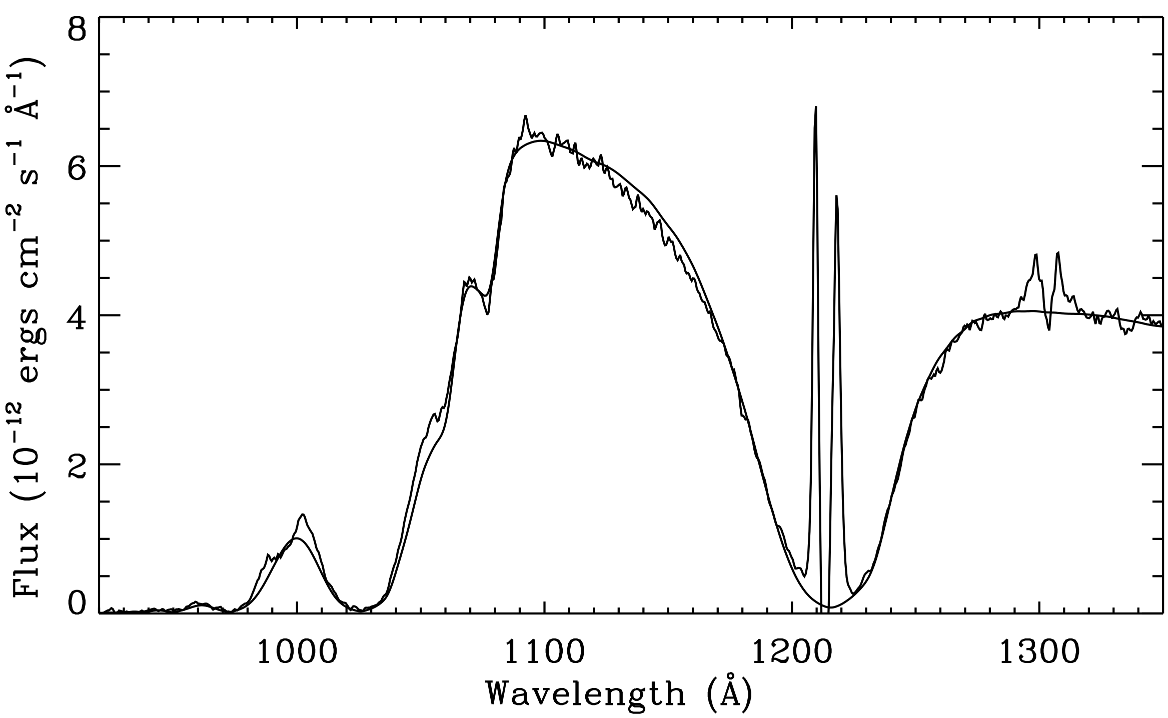

Fig. 4.— Lβ and Lα region of the background-subtracted HUT spectrum compared with a theoretical model (smooth curve) with the new Lβ broadening including the quasi-molecular satellites and $T_{\rm eff}$ = 20000 K, log g = 7.90.

Fig. 4 shows the result of this calculation compared to the observation, using our adopted values for $T_{\rm eff}$ and log g (20000/7.90). The model was scaled using the V magnitude, with an additional scale factor of 1.03 being applied to match the observed continuum flux longward of Lα. A slightly hotter model ($T_{\rm eff}$ = 21000 K) did not give a good fit to the data. The continuum flux for the hotter model (scaled to V) was 10% higher than observed and the Lα line was far too weak.

6. Conclusions

We have not made an effort to find the best fitting UV model, and the fit is clearly not perfect, especially in the region between Lα and Lβ. We have made some experiments and our conclusion is that far wing absorption of Lγ and higher Lyman lines, which are still calculated with standard Stark broadening, are part of the problem. Fig.4, however, clearly proves, by the coincidence of position and shape, that the two observed features near 1060 and 1078 Å are indeed satellite features of Lβ, and that the steep rise of the wing is caused by the exponential decline of the line profile beyond the last satellite. Further detailed studies of the line profiles of all Lyman lines will hopefully improve the quantitative agreement in the future, whereas new observations of hotter and cooler objects should establish the range where these features are observable, and provide a challenge to experimental physicists to measure these line profiles in laboratory plasmas.

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Table 1: Allowed molecular transitions corresponding to the n=1 to n=3 transitions in the isolated H atom. The first column is a running number and the column labeled RP gives the numbers for the states as used by RP. The column labeled wt gives the relative weight. The last column indicates the position of a satellite, if there is one, in cm^{-1} from the line center, and as absolute wavelength position in Å.

No.	low	up	RP	wt	wing	$\Delta\omega$[cm^{-1}](λ [Å])	
1	$1s\sigma_g$	$4p\sigma_u$	1 - 5	1	blue		—
2	$2p\sigma_u$	$3s\sigma_g$	1 - 5	1	blue		—
3	$1s\sigma_g$	$3p\pi_u$	1 - 8	2	blue		—
4	$2p\sigma_u$	$4d\pi_g$	1 - 8	2	blue		—
5	$1s\sigma_g$	$6h\sigma_u$	1 - 7	1	red	-953	(1036)
6	$2p\sigma_u$	$5g\sigma_g$	1 - 7	1	red	-4696	(1078)
7	$1s\sigma_g$	$4f\pi_u$	1 - 9	2	red	-3124	(1060)
8	$2p\sigma_u$	$5g\pi_g$	1 - 9	2	red	-436	(1030)